CubeSat Infrared Atmospheric Sounder (CIRAS) NASA InVEST Technology Demonstration

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ABSTRACT

Infrared sounders measure the upwelling radiation of the Earth in the Midwave Infrared (MWIR) and Longwave Infrared (LWIR) region of the spectrum with global daily coverage from space. The observed radiances are assimilated into weather forecast models and used to retrieve lower tropospheric temperature and water vapor for climate studies. There are several operational sounders today including the Atmospheric Infrared Sounder (AIRS) on Aqua, the Crosstrack Infrared Sounder (CrIS) on Suomi NPP and JPSS, and the Infrared Atmospheric Sounding Interferometer (IASI) on the MetOp spacecraft. The CubeSat Infrared Atmospheric Sounder (CIRAS) is a NASA In-flight Validation of Earth Science Technologies (InVEST) program to demonstrate three new instrument technologies in an imaging sounder configuration. The first is a 2D array of High Operating Temperature Barrier Infrared Detector (HOT-BIRD) material, selected for its high uniformity, low cost, low noise and higher operating temperatures than traditional materials. The detectors are hybridized to a commercial ROIC and commercial camera electronics. The second technology is a MWIR Grating Spectrometer (MGS) designed to provide imaging spectroscopy for atmospheric sounding in a CubeSat volume. The MGS employs an immersion grating or grism, has no moving parts, and is based on heritage spectrometers including the OCO-2. The third technology is a Black Silicon infrared blackbody calibration target. The Black Silicon offers very low reflectance over a broad spectral range on a flat surface and is more robust than carbon nanotubes. JPL will also develop the mechanical, electronic and thermal subsystems for the CIRAS payload. The spacecraft will be a commercially available CubeSat. The integrated system will be a complete 6U CubeSat capable of measuring temperature and water vapor profiles with good lower tropospheric sensitivity. The low cost of CIRAS enables multiple units to be flown to improve temporal coverage or measure 3D Atmospheric Motion Vector (AMV) winds. CIRAS will launch in 2019 and is only a technology demonstration. However, what we learn will benefit future instruments that support operational weather forecasting and climate studies.

Keywords: Infrared, Sounding, CubeSat, Grating, Spectrometer

1. INTRODUCTION

Hyperspectral radiances measured from Low Earth Orbiting (LEO) infrared (IR) sounders including the NASA Atmospheric Infrared Sounder (AIRS)[1] on Aqua, the Cross-track Infrared Sounder (CrIS) on the Joint Polar Satellite System (JPSS), and the Infrared Atmospheric Sounding Interferometer (IASI) on MetOp, have among the highest impact of any measurement type when assimilated into operational weather forecast models.[2,3,4] LEO IR sounder radiances are used to retrieve temperature and moisture profiles with high vertical accuracy.[5] AIRS profiles have been used to validate water vapor distributions in climate models and confirm positive water vapor feedback to global warming.[6,7]

Key objectives of CIRAS are to demonstrate technologies for reducing the cost of future IR sounders, help mitigate a gap in hyperspectral IR sounder coverage in the event of a loss of one of the current IR sounders, offer the opportunity for IR sounding data from new orbits, and maintain continuity of current IR sounders into the future. NASA has funded the CIRAS under the Inflight Validation of Earth Science Technology (InVEST) program under the Earth Science Technology Office (ESTO)[8,9]. The CIRAS is currently under development at NASA JPL and is scheduled for launch in 2019. The payload uses a mix of commercial and custom hardware to measure the upwelling spectrum in the MWIR for temperature and water vapor sounding. CIRAS technology will also be useful in a future 3-satellite constellation designed to measure IR water vapor Atmospheric Motion Vector (AMV) winds in 3D (due to the 3D nature of the water vapor retrievals). The CIRAS spacecraft will be a commercial 6U CubeSat developed by Blue Canyon Technologies (BCT).

Maintaining continuity of important IR sounder weather forecasting and climate data sets is critical to NASA and NOAA. NOAA has identified the need for an Earth Observation Nanosatellite - IR (EON-IR) as a low cost-to-orbit way to mitigate a potential gap in data of the CrIS on JPSS and offer new orbit opportunities. CIRAS will demonstrate the MWIR portion of EON-IR. The LWIR may not be required for some applications, yet development of the LWIR spectrometer and detector is part of JPL's technology path to a full MWIR/LWIR EON-IR.

2. INFRARED SOUNDER MEASUREMENTS AND DATA PRODUCTS

Infrared sounders measure the upwelling radiance in the infrared as shown in Figure 1. Atmospheric absorption features can be seen and the corresponding constituents are indicated. The radiances in the CO_2 and H_2O bands from the IR sounders have among the highest impact of any measurement type when assimilated into operational weather forecast models. As mentioned above, the radiances are also used to retrieve temperature and moisture profiles with high accuracy. Additional geophysical parameters measured include surface temperature, cloud properties, aerosols, and trace gases such as ozone, carbon monoxide, methane, ammonia and carbon dioxide. All parameters are acquired globally on a daily basis. See Figure 2.

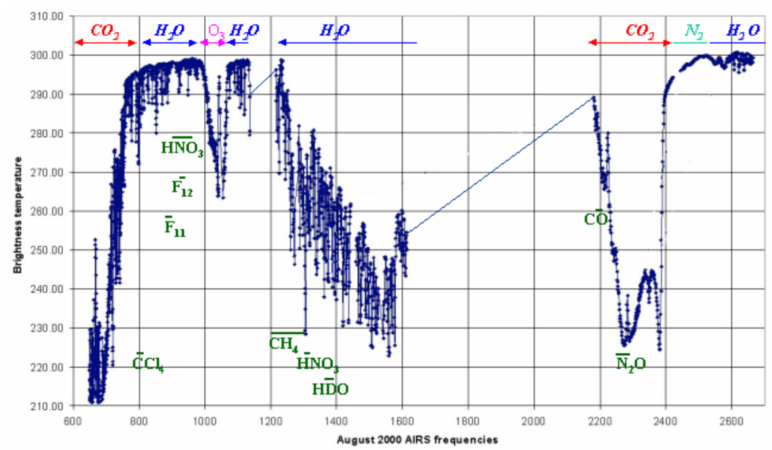


Figure 1. AIRS spectrum and atmospheric constituents contributing to the observed features. Temperature profiles are retrieved by sounding along the large CO_2 branches at 700 cm^{-1} and 2400 cm^{-1}.

As an example, a list of the primary AIRS standard deliverable products from Version 6.0 are given in Table 1. The performance of the product is listed in the third column. The fourth column identifies if these products can be achieved by the pathfinder CIRAS. All products are expected to be achieved by the future EON-IR. The products are divided into three types. Core radiances that consist of calibrated and geolocated upwelling radiances at the native resolution of the instrument (15 km). The second type of data are the Core Geophysical (Level 2) products. These products are geolocated geophysical quantities, usually offered on the scale of approximately 45 km at nadir. The third type of products are research products (at a low state of validation). Level 3 products are gridded spatially (1 degree latitude and longitude bins) and temporally (1 day, 8 day and monthly) and usually contain all standard Level 2 products. Level 3 products are produced for all geophysical variables. In addition to the products identified in the table that CIRAS can achieve, it is expected that a 3-satellite constellation of CIRAS operated in zoom mode (3 km resolution over a swath of 150 km) would produce good AMVs. The retrieval process would be similar to MODIS, but with 3D information due to the sounder vertical resolution (vs MODIS total column) and better coverage due to overlap at all latitudes. A broader swath is possible with reduced resolution and wind speed accuracy.

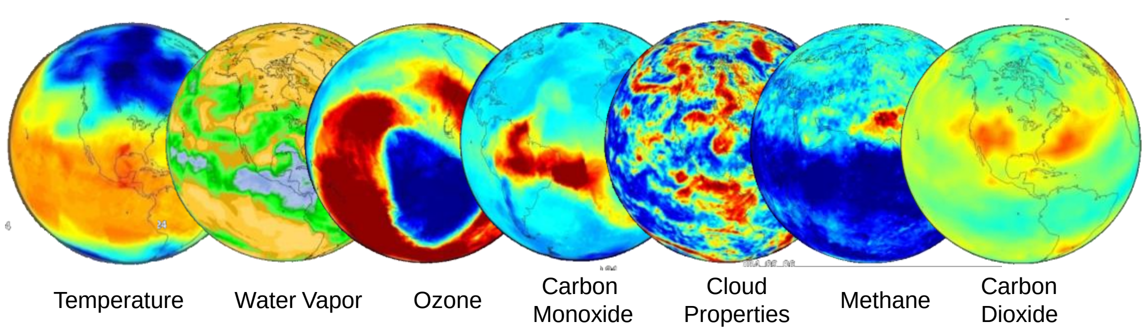


Figure 2. IR sounders create global maps of atmospheric temperature and water vapor and key gases

Table 1. Example of data products from a fully operational sounder (AIRS). Products achievable by CIRAS are identified. All products are expected to be achieved by EON-IR.

AIRS Product	Product Type	Accuracy (V5)	CIRAS
Core: Radiances			
AIRS IR Radiance	L1B-AIRS	<0.2K @ 250K	MWIR Only
AIRS VIS/NIR Radiance	L1B-VIS	15-20%	N/A
Core: Geophysical			
Cloud Cleared IR Radiance	L2	1.0 K	No
Sea Surface Temperature	L2	1.0 K	Yes
Land Surface Temperature	L2	2-3 K	Yes
Temperature Profile	L2	1 K / km	Yes
Water Vapor Profile	L2	15% / 2km	Yes
Total Precipitable Water	L2	5%	No
Fractional Cloud Cover	L2	20%	Yes
Cloud Top Height	L2	1 km	Yes
Cloud Top Temperature	L2	2.0 K	Yes
Carbon Monoxide	L2	15%	Yes
Carbon Dioxide (Mid-Troposphere)	Post-Proc	1-2 ppm	No
Total Ozone Column	L2	5%	No
Ozone Profile	L2	20%	No
Land Surface Emissivity	L2	10%	MWIR Only
IR Dust	L1B-Flag	0.5 K	No
Research Products			
Methane	L2	2%	No
OLR	L2-Support	5 W/m2	No
HNO3	L1B-Post	0.2 DU	No
Sulfur Dioxide	L1B-Flag	1 DU	No

3. TODAY'S OPERATIONAL SOUNDERS

Table 2 lists the primary characteristics of the infrared sounders currently in orbit. The first of these, AIRS, is currently operational and is expected to last the life of the spacecraft to 2022. In addition to operation on Suomi NPP, CrIS is scheduled for manifest on JPSS-1, 2, 3 and 4, continuing the measurement to the late 2030 timeframe. IASI is currently operational on Metop A and B and planned for operation on Metop C continuing the measurement through the 2024

Table 2. Currently operational infrared sounders in orbit today

Sounder Comparison	AIRS	IASI	CrIS
Spatial			
Orbit Altitude	705 km	817 km	824 km
Scan Range	±49.5°	±48.3°	±48.3°
Horizontal Resolution	13.5 km	12 km	14 km
Spectral			
Method	Grating	FTS	FTS
Nominal Resolution	0.5-2.5 cm^{-1}	0.5 cm^{-1}	1.0-5.0 cm^{-1}
0.4 - 1.0 um	4 Bands	n/a	n/a
1.0 - 3.0 um	n/a	n/a	n/a
3.0 - 5.2 um	3.7-4.6 μm (514)	3.6-5.2 μm (3348)	3.9-4.6 μm (632)
5.2 - 8.2um	6.2-8.2 μm (602)	5.2-8.2 μm (2814)	5.7-8.2 μm (864)
8.2 - 12.5 um	8.8-12.7 μm (821)	8.2-12.5 μm (1678)	9.1-12.0 μm (472)
12.5 - 15.5 um	12.7-15.4 μm (441)	12.5-15.5 μm (620)	12.0-15.4 μm (240)
Total Channels	2382	8460	2208
Radiometric			
NEdT	0.07-0.7K	0.25-0.5K	0.1-1.0K
Resources			
Size	1.4 x 0.8 x 0.8 m^3	1.2 x 1.1 x 1.3 m^3	0.9 x 0.9 x 0.7 m^3
Mass	177 kg	236 kg	165 kg
Power	256 W	210 W	117 W
Max Data Rate	1.3 Mbps	1.5 Mbps	1.5 Mbps

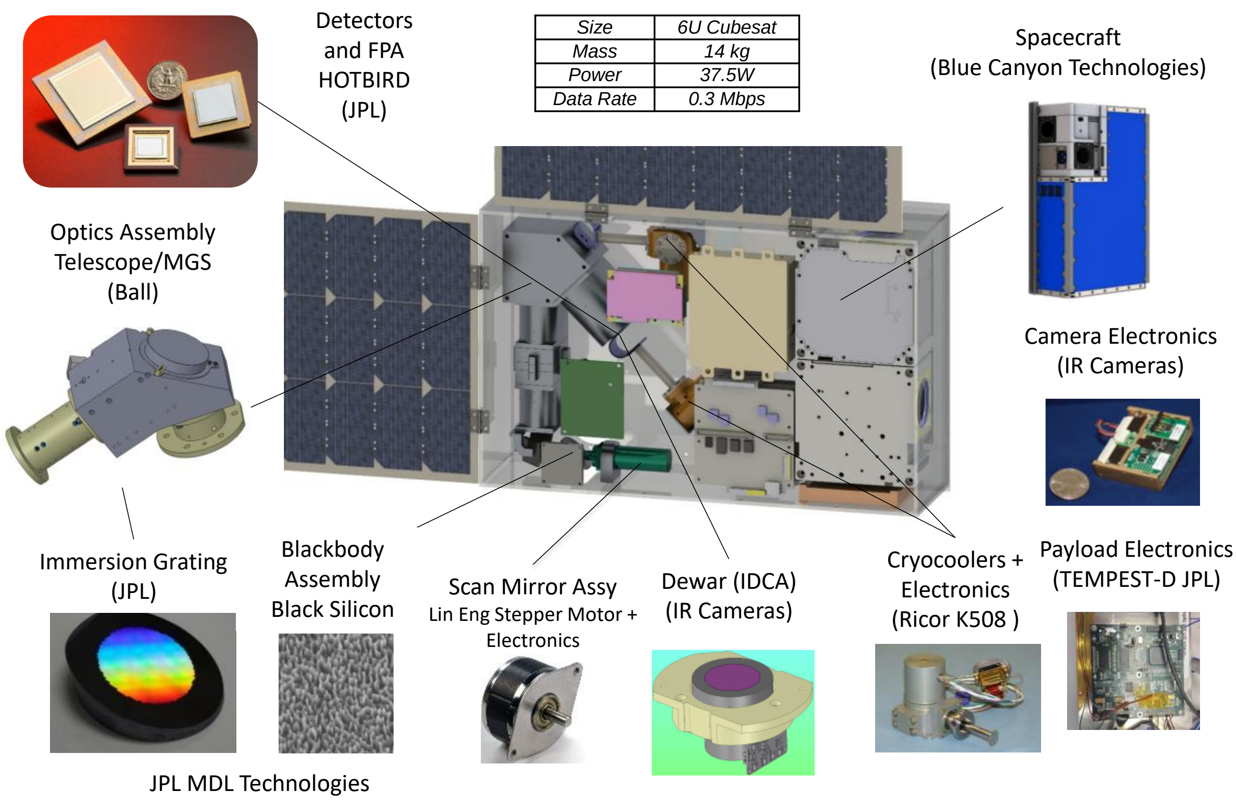
timeframe; after this time, the EUMETSAT Polar System Second Generation (EPS-SG) will most likely continue the measurement, but with a next generation infrared sounder. CrIS and IASI were developed later than AIRS and use a Fourier Transform Spectrometer for spectral separation, while AIRS uses a Grating Spectrometer. Both types have their advantages and disadvantages, however all these instruments are considered fully operational, reliable and have exceptional performance. All of these instruments weigh over 150kg and require over 100W, but CrIS uses the fewest spacecraft resources.

4. THE CUBESAT INFRARED ATMOSPHERIC SOUNDER

The CIRAS instrument (Figure 3) includes a scan mirror capable of rotating 360º to view Earth, cold space and an internal blackbody for calibration. The Scan Mirror Assembly consists of a single planar gold coated aluminum mirror mounted at 45º to the axis of a stepper motor. Gold provides low polarization and high reflectance in the CIRAS band. Footprint rotation is not a concern since all spectral channels share the same slit (same for AIRS), and slit rotation angle is deterministic, making geolocation straightforward. The blackbody is a simple flat plate composed of Black Silicon, heat sunk and instrumented with a temperature sensor, and provides high emissivity and durability in a compact design. Energy from the scan mirror is collected using a 3-element all-refractive telescope. Energy from the telescope is focused onto the entrance slit of an all refractive MWIR Grating Spectrometer (MGS). The telescope and spectrometer are under development by Ball Aerospace. The spectrometer disperses the energy across the spectral range and produces a 2-dimensional image at the focal plane with one direction spatial (504 pixels) and the other spectral (625 channels).

The detector array uses the JPL HOT-BIRD photosensitive material mounted on a Lockheed Martin Santa Barbara Focalplane (SBF) 193 Readout Integrated Circuit (ROIC). The ROIC is mounted in a custom Integrated Dewar Cryocooler Assembly (IDCA) to be developed by IR Cameras. The dewar contains a cold filter mounted in close to the focal plane, and a window at the interface between the dewar and the optics.

The CIRAS subsystem electronics are primarily commercial. A payload electronics board will be developed to interface the various subsystems. Clocks, biases and A/D conversion are performed using military-grade electronics also provided



Size	*6U Cubesat*
Mass	*14 kg*
Power	*37.5W*
Data Rate	*0.3 Mbps*

Figure 3. The CubeSat Infrared Atmospheric Sounder (CIRAS)

by IR Cameras. JPL will develop the payload electronics to interface with the scanner, camera, cryocoolers, blackbody and spacecraft electronics.

Cooling of the spectrometer to 190K and the narrow spectral range of the filters minimize background loading on the detector. The optics are cooled using a Ricor K508 cryocooler. The detector is cooled to 115K, also using a Ricor K508 cryocooler. Both are heat sunk to the spacecraft chassis. Electronics, cryocooler and spacecraft waste heat is dissipated in warm temperature radiators on all unused surfaces.

CIRAS will be developed as a stand-alone payload with mechanical, thermal, and electrical interfaces to the spacecraft. The CIRAS spacecraft will be a commercial 6U system developed by Blue Canyon Technologies (BCT) with deployable solar panels and extra batteries. The spacecraft will provide communications, navigation, power and on-board processing and formatting of the raw data stream from the payload. The spacecraft structure will have custom features to allow a clear scan field of view and for mounting the payload components.

Additional details of the design are included in prior writings[8,9].

4.1 CIRAS Requirements

Table 3. AIRS Performance and CIRAS Requirements. CIRAS focuses on the lower troposphere.

Parameter	AIRS Performance	CIRAS Requirement
Vertical Range	1000-100mb	1000-300 mb
Temperature Profile	≤1.5 K/km	≤1.5 K/km
Humidity Accuracy	15%/2km	20%/2km
Spectral Range	3.7-15.4μm	4.08-5.13μm
Spectral Resolution	≤0.5-2.2cm^{-1}	≤ 1.2-2 cm^{-1}
Spatial Res. (nadir)	13.5 km	13.5 km
Scan Range	1750 km	1100 km
NEdT	0.1-1.0K	<0.25K
Size	1.4 x 0.8 x 0.8 m^3	6U
Mass	177 kg	10 kg
Power	256W	40 W

Table 3 shows the performance capability of AIRS (similar for CrIS) compared to the requirements for CIRAS. The legacy sounders and CIRAS achieve relatively low spatial resolution, 13.5 km, but have a broad swath for global daily revisit. The CIRAS orbit altitude is lower than AIRS and CrIS (between 450-600 km) contributing to a reduced swath. The pixel aggregation approach for CIRAS allows the same resolution to be achieved for any orbit altitude. A zoom mode allows 3 km over a 150 km swath achievable by a change in scan rate and binning.

The spectral band for CIRAS only covers the MWIR. This allows minimum resource requirements from the instrument while still achieving a good temperature and water vapor profile. The spectral resolution of CIRAS is comparable to legacy sounders in this band providing similar vertical resolution in the lower troposphere[8]. The band includes 2 temperature sounding branches and goes well into the water continuum.

Lower spectral resolution and lack of the LWIR impact vertical sensitivity to temperature and water vapor, but the differences are small, particularly in the lower troposphere. Currently there are two Observing System Simulation Experiments (OSSEs), one sponsored by NOAA performed at the University of Wisconsin, and another sponsored by NASA performed at the Global Modelling and Assimilation Office (GMAO) at GSFC to evaluate the impact of assimilation of MWIR-Only radiances on forecast accuracy, since the LWIR channels in the IR sounders are currently being used for temperature and water vapor sounding. Simulations of retrievals using the MWIR-Only in AIRS have shown good results in the lower troposphere[10]. Maturation of the radiative transfer models and additional assimilation studies are needed in the MWIR to make full use of this band in the data that currently exists in the IR sounders today. The legacy sounders achieve temperature sounding well into the stratosphere using the LWIR, although similar data in the stratosphere is achieved from microwave sensors. Addition of the LWIR is possible in future instruments with additional volume and power.

4.2 CIRAS Technology Development Status

There are three key technologies to be demonstrated by CIRAS that enable standard and high spectral resolution measurements in the infrared from space. The first is an infrared spectrometer operating in the MWIR that employs all refractive elements and an immersion grating to reduce optical distortion and packaging size. Second is an infrared detector material that provides high uniformity, low dark current and high sensitivity. These detectors have never flown in space, and CIRAS will demonstrate their utility in acquiring sounding data. Third is a new material called ‘Black Silicon’, which provides high emissivity over a broad spectral range.

4.2.1 Optics

The CIRAS optical design includes the all refractive wide field telescope and the MWIR Grating Spectrometer (MGS). The all refractive design with multiple elements enables good image and color correction over a large, two dimensional field of view. Two important requirements of spectrometer optical performance are the spectral ‘smile’ (<2 pixels) and keystone geometrical distortions (<2 pixels). Better than 1 pixel is achieved in the design. CIRAS mitigates optical distortion by oversampling the spectrum at Nyquist and oversampling the spatial at 42x using a large format detector array (640 x 512 elements), and resampling the image plane to a rectilinear grid. This requires good pre-flight characterization and modeling of the image at the focal plane.

Figure 4. JPL/Ball SIRAS IIP-2000 LWIR Spectrometer.

The CIRAS is based on designs developed by JPL and Ball Aerospace in the late 1990’s and mid 2000’s. The Spaceborne Infrared Atmospheric Sounder (SIRAS)[11] and SIRAS-Geosynchronous Earth Orbit (SIRAS-G) demonstrated wide field all refractive grating spectrometer systems operating in the LWIR and MWIR respectively with spectral resolution and field of view comparable to the CIRAS. Figure 4 shows the SIRAS LWIR spectrometer developed by Ball Aerospace and JPL in 2000. CIRAS is much smaller and simpler than the SIRAS spectrometers and will also be developed at Ball Aerospace with the immersion grating and entrance slit developed at JPL. A silicon immersion grating similar to that required for CIRAS has been developed in the JPL Micro Devices Laboratory (MDL) for the OCO-WF RTD program. Measurements show the diffracted beam at the predicted angles and required efficiencies. JPL will also develop the entrance slit for the spectrometer using JPL’s Black Silicon texturing technology. A preliminary design of the optics are complete and meet performance requirements.

4.2.2 HOT-BIRD Detectors

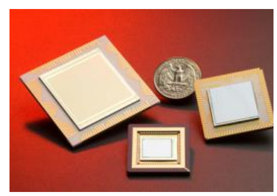


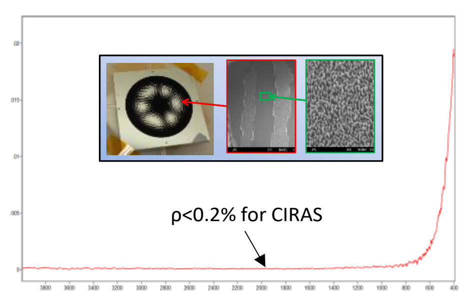
Figure 5. HOT-BIRD Detectors made at JPL

CIRAS will use the recently invented JPL High Operating Temperature Barrier Infrared Detector (HOT-BIRD) technology based on III-V compounds. HOT-BIRD offers a breakthrough solution for the realization of lower development cost, while reducing dark current and improving uniformity and operability compared to II-VI material (MCT). Low 1/f noise[12] and high temporal stability allows CIRAS to use a slow scan for better sensitivity and less frequent calibrations. Using the HOT-BIRD material, JPL has fabricated a variety of MWIR and LWIR FPAs with different pixel pitches (12µm and above) and formats (up 1Kx1K), see Figure 5. Detector material for CIRAS has been manufactured that meets dark current requirements with good margin. Detectors are in hybridization processing at the time of this writing.

4.2.3 Black Silicon Blackbody and Slit

AIRS used a wedge calibration blackbody, which is excellent and robust, but large. In order to save space the CIRAS calibration target (blackbody) is a flat plate coated with a JPL developed Black Silicon process. The result is a broadband black surface, exhibiting less than 0.15% reflectance at a wavelength of 5 microns. (Figure 6). The calibration target will be mounted to an aluminum block with a temperature sensor and operate at ambient temperatures. Temperature sensing accuracy is expected to be better than the 0.25K requirement. Black silicon is used for stray light absorption on the OCO-2 spectrometer slit currently flying in space. The CIRAS Black Silicon components are in the design phase.

Figure 6. Cryo-etched Black Si reflectance. Inset: WFIRST-AFTA high contrast apodizer



5. SUMMARY AND CONCLUSIONS

Infrared sounders provide high impact to weather forecast model predictions by providing high vertical resolution temperature and water vapor information with global daily coverage at modest resolution of 13.5 km. Legacy sounders including AIRS, CrIS and IASI provide good measurements that collectively are expected to last through the late 2030's. The CubeSat Infrared Atmospheric Sounder will demonstrate, in space, key technologies for future infrared imaging and sounding remote sensing instruments (e.g. EON-IR) to serve as a backup to the operation sounders, provide additional measurements at different times of the day, or measure new products including 3D AMVs. By measuring the hyperspectral infrared spectrum only in the MWIR, we are able to fit it in a 6U CubeSat. The MWIR by itself provides sufficient information to produce data products, but assimilation studies have not yet completed their assessment of the impact to forecast models. CIRAS incorporates new technologies including a wide field MWIR Grating Spectrometer (MGS) employing an immersion grating, HOT-BIRD detectors, and a Black-Silicon blackbody. These new technologies combined with commercial technologies in camera and payload electronics, scanning, cryocooling and the spacecraft enable the CIRAS to be developed at low cost and in a CubeSat configuration. CIRAS is under development by JPL with industry partners including Ball Aerospace for the MGS, IR Cameras for the IDCA, and Blue Canyon Technologies for the Spacecraft. CIRAS is scheduled for launch in 2019.

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REFERENCES

[1] Pagano, T. S., M.T. Chahine, E.J. Fetzer, "The Atmospheric Infrared Sounder (AIRS) on the NASA Aqua Spacecraft: a general remote sensing tool for understanding atmospheric structure, dynamics and composition" Proc. SPIE 7827-11, (2010).

[2] Cardinali, C, "Monitoring the observation impact on the short-range forecast" QJR Met Soc 135, 239–250 (2009)

[3] J. Le Marshall, J. Jung, M. Goldberg, C. Barnet, W. Wolf, J. Derber, R. Treadon and S. Lord, "Using cloudy AIRS fields of view in numerical weather prediction" Aust. Meteorological Magazine 57, 249-254 (2008).

[4] McNally, A.P., Watts, P.D., Smith, J.A., Engelen, R., Kelly, G.A., Thepaut, J.N., and Matricardi, M., "The assimilation of AIRS radiance data at ECMWF" QJR Meteorol. Soc. 132, 935-957. doi: 10.1256/qj.04.171 (2006).

[5] Susskind, J., J. M. Blaisdell, and L. Iredell, "Improved methodology for surface and atmospheric soundings, error estimates, and quality control procedures: the AIRS science team version-6 retrieval algorithm" J. Appl. Remote Sens. 8(1), 084994 (2014).

[6] Pierce D. W., T. P. Barnett, E. J. Fetzer, P. J. Gleckler, "Three-dimensional tropospheric water vapor in coupled climate models compared with observations from the AIRS satellite system" Geophys. Res. Lett. 33, L21701, doi:10.1029/2006GL027060. (2006).

[7] Dessler, A. E., Z. Zhang, and P. Yang, "Water-vapor climate feedback inferred from climate fluctuations, 2003-2008" Geophys. Res. Lett. 35, L20704, doi:10.1029/2008GL035333. (2008)

[8] Pagano, T. S., D. Rider, M. Rud, D. Ting, K. Yee, "Measurement approach and design of the CubeSat Infrared Atmospheric Sounder (CIRAS)", Proc. SPIE 9978-5, San Diego, CA (2016)

[9] Pagano, T. S. et al., "The CubeSat Infrared Atmospheric Sounder (CIRAS), Pathfinder for the Earth Observing Nanosatellite-Infrared (EON-IR)" Proc. AIAA/USU Conference on Small Satellites SSC16-WK-32, (2016)

[10] Pagano, T.S., Aumann, H., Gerber, A., Kuai, L., Gontijo, I., DeLeon, B., Susskind, J., Iredell, L., Bajpai, S., "Requirements for a Moderate-resolution Infrared Imaging Sounder (MIRIS)", Proc. SPIE 8870-7, San Diego, CA (2013)

[11] Kampe, T., T. Pagano, J. Bergstrom, "SIRAS, The Spaceborne Infrared Atmospheric Sounder: an approach to next-generation infrared spectrometers for Earth remote sensing" Proc. SPIE 4485 (2002).

[12] Gunapala, Sarath, et al., "1/f Noise QWIPs and nBn Detectors" Proc. QSIP (2014)